OD-MAC: An On-demand MAC Protocol for Body Sensor Networks Based on IEEE 802.15.4

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Abstract

A Body Sensor Network (BSN) is a network of sensors that sense vital signs of a human body. The vital signs can be divided into two categories based on significance to the life: critical and non-critical signs. The critical vital signs, or real-time messages (RTMs), should be transmitted within the deadlines, and they must not be collided. On the other hand, the non-critical signs, or non-real-time messages (NRTMs), are required to be delivered with the best effort. In this paper, an on-demand MAC (OD-MAC) is proposed for BSN to provide real-time transmission, collision avoidance, and energy efficiency. The protocol is developed on IEEE 802.15.4 standard, and some specifications are modified to support those requirements. The OD-MAC changes the superframe structure dynamically to schedule RTMs and NRTMs. Those messages request bandwidth, and the network coordinator adaptively changes beacon interval and allocates slots to the messages. For evaluating the performance, duty cycle according to required utilization, delivery ratio, and energy efficiency are analyzed with simulations using NS2.

Keywords: *on-demand MAC, Body Sensor Networks, Sensor Networks, IEEE 802.15.4*

1. Introduction

Advances of Wireless Sensor Network (WSN) technologies enabled to sense and transmit vital signs of human, such as electrocardiograph, electromyography, and blood pressure. A network of those tiny bio-medical sensors is called Body Sensor Network (BSN), and it can be used in many application areas. Remote healthcare system, wireless intensive care system in hospital, and soldier monitoring system for military are the examples. For those BSN applications, network protocols are important for reliable communications; especially, MAC protocol has been focused on this paper.

Body Sensor Networks has been researched actively in many universities and research institutes. CodeBlue project [3] has worked on platform and sensors, and they have developed several applications for medical care. Also, MobiHealth project [4] has researched about remote healthcare systems. The project group has integrated BSN to GPRS/UMTS mobile network. However, they are not focusing on developing MAC protocols of BSNs, and a few MAC protocol have been developed in other research groups.

In BSN systems, sensing data are critical to human life, and the data should be transmitted in reliable and real-time manner for immediate and accurate diagnoses. Also, energy efficiency and adaptivity are required. The sensors are powered by batteries, and they can be implanted to body. Changing batteries of the implanted sensors is dangerous since it shall need a big surgery, so energy efficiency should be supported. Moreover, adaptivity is required to satisfy network conditions in terms of changing number of nodes and their bandwidth request.

I. E. Lamprinos et al. [5] developed a time division multiple access (TDMA) protocol for energy efficiency. They designed a new frame format to reduce idle listening, collision, and energy outspending, but the protocol is developed for general WSNs rather than BSNs.

Huaming Li et al. developed BSN-MAC [6] and H-MAC [7] with considering the characteristics. For BSN-MAC, they adopted priority based scheme based on IEEE 802.15.4 MAC standard. The priority of a sensor node is determined depending on the criticalness

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of its sensor, and the sensor node with higher priority can access the medium first. However, the priorities of sensors are determined implicitly. H-MAC proposed a TDMA protocol with a new synchronization scheme. It synchronizes the time of sensor nodes using heart beats of human body. The sensors check peaks of heart beat signals, and synchronize the time on it. H-MAC used a unique characteristic (i.e. heart beats) of body, but the sensor nodes require additional hardware to detect heart beat signals. Moreover, operating the hardware consumes extra energy.

In this paper, an on-demand MAC (OD-MAC) protocol is proposed to support the four primary requirements of BSN MAC: real-time transmission, collision avoidance, energy efficiency, and adaptivity. The OD-MAC is developed based on IEEE 802.15.4 standard [1] with some modifications of specifications. The OD-MAC satisfies real-time transmission and collision avoidance with using guaranteed time slots, and energy efficiency and adaptivity are supported by adjusting durations of the superframes. In other words, the superframe structure of the OD-MAC dynamically changes according to demands of messages. It changes beacon interval and allocates slots for scheduling RTMs, and it adjusts superframe duration with increasing or decreasing the superframe order (SO) to satisfy required bandwidth utilization of NRTMs. The performance of the protocol is evaluated with simulations using NS2. Duty cycle changes according to total required bandwidth utilization, delivery ratio, and energy efficiency are measured to evaluate the allocation algorithm for NRTMs.

For the remaining part of this paper, section 2 overviews IEEE 802.15.4 specifications. Also, the main ideas of the OD-MAC are explained in section 3, and section 4 describes the major modifications of specifications. Section 5 shows the results of performance evaluation, and section 6 concludes the paper finally.

2. Overview of IEEE 802.15.4 superframe

The MAC protocol of IEEE 802.15.4 standard can be operated in both beacon enabled mode and non-beacon mode. Especially, an optional superframe in beacon enabled mode is composed of beacon, contention access period (CAP), contention free period (CFP), and inactive period. Figure 1 shows the optional superframe structure.

The optional superframe provides a hybrid mechanism of TDMA and slotted CSMA-CA, and it makes the MAC protocol adaptable. The CFP with guaranteed time slots (GTSs) supports TDMA for messages which need real-time transmission. Also, any sensor nodes in the PAN can access slots in CAP by contention. The network coordinator determines superframe duration with superframe order (SO), and the size of each slot is adjusted according to the SO. Moreover, the coordinator determines beacon interval (BI) with beacon order (BO).

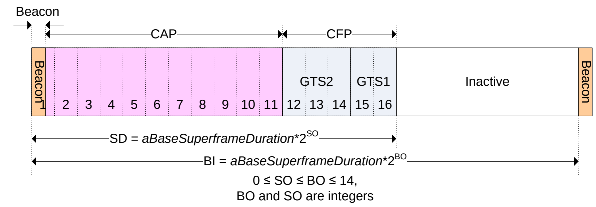


Figure 1. IEEE 802.15.4 optional superframe

The superframe structure of IEEE 802.15.4 has several limitations to be used for BSNs. In BSNs, sampling period, data length, or required bandwidth utilization of messages can be changed by applications. Also, sensor nodes can join or leave the network, so the superframe structure of a MAC protocol should be managed dynamically. However, that of the standard is managed statically. BO and SO are determined when the networked is initialized and not changed in run time. Therefore, it cannot handle the changing requirements of messages, and its static superframe duration wastes energy when the required utilization of NRTMs is less than the determined duration. Also, the number of GTSs is limited up to 7, so it can schedule just a few RTMs. In order to overcome these limitations, OD-MAC supports dynamic reconfiguration of the superframe structure.

3. OD-MAC protocol

The OD-MAC is designed with modification and addition of some specifications to support the requirements; real-time transmission, collision avoidance, energy efficiency, and adaptivity. Instead of using static BO and SO, the OD-MAC dynamically reconfigures superframe structure in run time according to bandwidth requests of sensor nodes. It varies BI to support real-time requirements, and increase or decrease SD to provide energy efficiency and adaptivity.

The on-demand MAC (OD-MAC) is developed based on IEEE 802.15.4 MAC standards. It is operating on 2.4GHz RF band with star topology, and the maximum number of node is 255. Also, the network coordinator is a full-function device (FFD), and sensor nodes work as reduced-function devices (RFDs). Each node has one type of sensor, and the sensor nodes can request and send one type of message. Moreover, sampling period or data length can be changed by application in run time.

In this protocol, sensor nodes can transmit two types of messages: real-time message (RTM) and non-real-time message (NRTM). Also, all the messages, except control messages, shall be periodically transmitted. Sensor nodes which sense time-critical vital signs, such as nodes for severe medical applications, transmit RTMs, and nodes with non-time-critical information, which are for rehabilitation applications, send NRTMs. The RTMs request GTSs to the coordinator with sampling period and data length as parameters. Also, the NRTMs request CAP slots with required bandwidth utilizations, or RU, in percentage. The sensor nodes with NRTMs estimate the required utilization based on current BI and their data length. The message sets and the input parameters are described below:

$$RTM = \{RTM_0, RTM_{1, \ldots,} RTM_{n-1}\}$$
$$RTM_i = \{SP_i, DL_i\}, \quad i = 0, 1, \ldots, n-1$$
$$NRTM = \{ NRTM_0, NRTM_1, \ldots, NRTM_{n-1}\}$$
$$NRTM_i = \{RU_i\}, \quad i = 0, 1, \ldots, n-1$$

For example, a node *i*, which wants to transmit real-time messages, sends $RTM_i = \{3000, 4\}$ to the coordinator, and another node *k*, which wants to send non-real-time message and requires 1% of bandwidth utilization, requests $NRTM_k = \{1\}$. When a message arrives, the OD-MAC reconfigures the superframe dynamically, and Figure 2 depicts an example of the superframe reconfiguration.

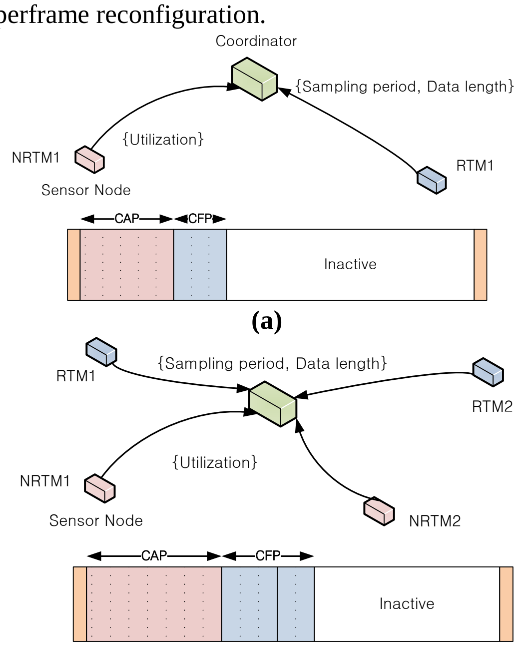


Figure 2. An example of superframe reconfiguration

Table 1 shows the notation defined to be used for the models and algorithms.

Table 1. Notations

Notation	Description
SP	Required sampling period in usec. SP = $\{SP_0, SP_1, \ldots, SP_{n-1}\}$
SPS	Required sampling period in symbol. SPS = $\{SPS_0, SPS_1, \ldots, SPS_{n-1}\}$
SPH	Sampling period after harmonization. SPH = $\{SPH_0, SPH_1, \ldots, SPH_{n-1}\}$
DL	Required data length of a message in byte. DL = $\{DL_0, DL_1, \ldots, DL_{n-1}\}$
DLS	Required data length of a message in symbol. DLS = $\{DLS_0, DLS_1, \ldots, DLS_{n-1}\}$
SL	Required slot length of a RT/NRT message.
BO	macBeaconOrder. ($1 \leq BO \leq 14$)
SO	macSuperframeOder. (Initial value = 0, $SO \leq BO$)
BIO	Beacon Interval Order. Determined by harmonization
odNumSFSlot	Number of superframe slots.
BnCAPSlot	Allocated slots for beacon and CAP
U	Total utilization for GTS scheduling
RU	CAP utilization required in percentage.
TRU	Total required CAP utilization in percentage.
T_S	Symbol duration. (16usec@2.4GHz)
MT_{ACK}	Maximum acknowledgement response time. (aTurnaroundTime + aUnitBackoffPeriod) symbols.
MF	Major frame.
mf	Minor frame.
O_F	Frame overhead, or MAC-sublayer overhead.
O_P	Packet overhead, or PHY-layer overhead.
O_{ACK}	Acknowledgement overhead.
O_{IFS}	Interframe space overhead.
O_{TOTAL}	Total overhead.

3.1. GTS allocation algorithm

The GTS scheduling of the OD-MAC is composed of four steps: BI determination, harmonization, schedulability test, and optimization step.

3.1.1. Step 1: BI determination

The equation of BI of the OD-MAC is different from the standard. Instead of multiplying 2^{BO}, it uses BO because this way can adjust BI to the required sampling intervals. Also, the number of superframe slot, denoted as *odNumSFSlot*, is not fixed to 16, but it varies according to the requests. Equation (1) denotes the BI.

The superframe duration (SD) of this protocol is defined as (2). SO is initially set to 0, and the protocol changes SO to adjust SD. It makes the superframe can handle more messages, and it also can let the protocol energy efficient. When just a few nodes are existing in a network, CAP slots of the standard superframe might not be utilized 100%, and it causes energy waste. On the other hand, the OD-MAC changes the number of slots according to the request, so it can achieve better utilization and save energy.

$$BI = aBaseSlotDuration * odNumSFSlot * BO \quad (1)$$

$$SD = aBaseSlotDuration * odNumSFSlot * SO \quad (2)$$

$$SPS_i = \left\lfloor \frac{SP_i}{T_S} \right\rfloor \quad (3)$$

$$SL_i = \left\lceil \frac{DLS_i}{aBaseSlotDuration * 2^{SO}} \right\rceil \quad (4)$$

$O_F = 6 + 2 + 1 + 2;$
$O_P = 6;$
$O_{FP} = (O_F + O_P) * SpB;$
$O_{ACK} = MT_{ACK} + (5 + O_P) * SpB;$
$O_{IFS} = (DL_i + O_F \leq aMaxSIFSFrameSize)\ ?\ aMinSIFSPeriod : aMinLIFSPeriod;$
$O_{AI} = O_{ACK} + O_{IFS};$
$O_{TOTAL} = O_{FP} + O_{AI};$
$DLS_i = DL_i * SpB + O_{TOTAL};$

Figure 3. Process for changing DL to DLS

The OD-MAC determines BI according to SPS of the requested RTMs. If three RTMs are requested, which are $RTM_0 = \{1000000, 8\}$, $RTM_1 = \{1500000, 3\}$, and $RTM_2 = \{2100000, 2\}$, it first translates the SP and DL into symbols, or SPS and DLS. Before the translations, $SP = \{1000000, 1500000, 2100000\}$ and $DL = \{8, 3, 2\}$, and after the translations, the sets are changed to $SPS = \{62500, 93750, 131250\}$ by (3) and $DLS = \{136, 93, 92\}$ by Figure 3. Also, SL is determined as $\{3, 2, 2\}$ according to (4) because the size of a slot, or *aBaseSlotDuration*, is set to 60 symbols, and the value of *odNumSFSlot* shall be 15. (aMinCAPLength equals 440, and CAP and beacon needs 8 slots, so *odNumSFSlot* = 3 + 2 + 2 + 8.)

$$\begin{aligned} &MIN(SPS_i) - aBaseSlotDuration * odNumSFSlot \\ &\leq aBaseSlotDuration * odNumSFSlot * BO \leq MIN(SPS_i) \end{aligned} \quad (5)$$

BI shall be determined by (5). In the example, the minimum of *SPS* is SPS_1 which equals to 62500, and the candidate BOs are from 1 to 69. In this case, BO should be set to 69 (BI = 62100) in order to satisfy the requirements of RTMs and manage the superframe efficiently.

3.1.2. Step 2: Harmonization

After determining BI, a harmonization process [8] is required for the utilization of the superframe. When an RTM needs larger sampling period than double of the minimum required sampling period, slots for the RTM do not have to be allocated in every superframe. Therefore, the protocol allocates slots for the RTM in every *n* superframes, and this process is called harmonization. In the OD-MAC, SPH shall be set by the harmonization process as described in (6):

$$\begin{aligned} &BI * BIO \leq SPS_i \leq BI * (BIO + 1) \\ &SPH_i = BI * BIO \end{aligned} \quad (6)$$

Therefore, SPH would be set as $SPH = \{62100, 62100, 124200\}$ in the example. Also, Figure 4 depicts the harmonized superframe structure of the example. Each superframe is called mf, and the set of superframes which has cyclic repetition is called MF.

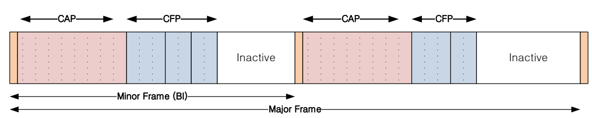


Figure 4. Harmonization of sampling periods

3.1.3. Step 3: Schedulability test

After processing the harmonization, the schedulability should be checked. If the total utilization of RTMs, beacon frame, the minimum CAP, and the inactive portion of a superframe does not exceed 1, the messages are always schedulable. The OD-MAC tests the schedulability with (7).

$$\begin{aligned} &U = \frac{BnCAPSlot}{BI / aBaseSlotDuration * SO} + \frac{BI - SD}{BI} + \sum_{i=0}^{n-1} \frac{DLS_i}{SPH_i} \\ &U \leq 1 \end{aligned} \quad (7)$$

In this equation, the first fraction is the utilization of the allocated slots for beacon and the minimum CAP, and the second fraction means the utilization of the inactive period. The last fraction is the total utilization of RTMs. The example is schedulable because the total utilization U = 61161/62100 which is less than 1, and it achieved 98.5% of utilization.

3.1.4. Step 4: Optimization

```
if U > 1 then
  if BO ≤ SO then
    set BO = BO − 1
    set SO = 0
    goto STEP 2
  else
    if SO + 1 < BO then
      set SO = SO + 1
      goto STEP 1
    end
  end
end
```

Figure 5. Optimization process

If the total utilization exceeds 1, the protocol executes the optimization process like the pseudo code described in Figure 5. If SO is larger or equal to BO, the coordinator decreases BO by 1 and sets SO to 0 then start the algorithm again from the step 2. If not, it increases SO by 1, which is still smaller than BO, and re-execute the whole process again.

3.2. CAP allocation algorithm

The CAP allocation algorithm shall be executed while GTS is schedulable. Sensor nodes which want to send NRTMs, they estimate their required bandwidth utilization in percentage based on given BI. In other words, each NRTM also has its sampling period and data length, but it does not send them as parameters, but it estimates its required utilization (RU) based on sampling period, data length, and BI. Then, it transmits a request message to the network coordinator with the parameter RU. Equation (8) shows the estimation.

$$RU_i = \frac{(BI/SPS_i) * DLS_i}{BI} * 100 \tag{8}$$

$$TRU = \sum_{i=0}^{n} RU_i \qquad TRU \le \frac{BI - SD}{BI} * 100 \tag{9}$$

Each node translates it sampling period and data length in symbol with the process we did for RTMs. Then, it estimates needed portion in BI, and sends it, as $NRTM_i = \{RU_i\}$, to the coordinator.

The coordinator stores the received NRTMs in the set $NRTM = \{NRTM_0, NRTM_1, \ldots, NRTM_{n-1}\}$ and estimates the total required utilization (TRU) then, it checks whether the TRU exceeds to inactive portion or not as (9). If TRU exceed, it shall be set to the maximum. In order to adjust SD, it changes SO in (2) according to the amount of TRU.

4. Modification of specifications

The OD-MAC is developed based on IEEE 802.15.4 MAC protocol, but there are some modifications of the specifications to apply the slot allocation algorithms. Several new MAC personal information base (PIB) attributes and network-sublayer management entity (NLME) primitives are added. Also, the formula of calculating BI and SD are changed like equation (1) and (2).

Table 2 shows the added MAC PIB attributes with identifier, type, range, description, and default value of each attribute. Especially, the attribute *odGTSInfo* is a collection of gotten GTS requests from RTMs. When the network coordinator executes GTS scheduling algorithm, it gets the parameters required for calculation and updates the attribute after finishing the algorithm. The format of *odGTSInfo* is depicted in Figure 6.

In addition, five MLME primitives are defined as follows:

- MLME-ODGTS.request{GTSCharacteristics, ODGTSCharacteristics}
- MLME-ODGTS.confirm{GTSCharacteristics, ODGTSCharacteristics, Status}
- MLME-ODGTS.indication{DevAddress, GTSCharacteristics, ODGTSCharacteristics}
- MLME-ODCAP.request{UtilizationRequest}
- MLME-ODCAP.indication{UtilizationRequest}

Octets: 2	2	1	1	1
Network Address	samplingPeriodSymbol	dataLength	slotLength	BIO

Figure 6. Format of odGTSInfo

Octets: 7	1	1	3
MHR fields	Command frame identifier	GTS characteristics	ODGTS characteristics

ODGTS request format

Octets: 2	1
samplingPeriodSymbol	dataLength

ODGTSCharacteristics field format

Octets: 7	1	1
MHR fields	Command frame identifier	Utilization Request

ODCAP request format

Figure 7. Frame formats of the new primitives

Table 2. New MAC PIB Attributes

Attribute	Identifier	Type	Range	Description	Default
odGTSInfo	0x60	Sets of octets	—	Store samplingPeriodSymbols, dataLengths, dataLengthSymbols, and BIOs of the member nodes for for the algorithm.	NULL
odBIO	0x61	Integer	1-255	Beacon Order Interval. If samplingPeriodSymbol is multiple of BI, allocate GTS according to interval.	1
odNumSFSlot	0x64	Integer	0-255	Number of superframe slots.	0
odSlotDuration	0x66	Integer	60-840	Duration of a slot is changed when SO changes.	60
CAPUtilization	0x69	Integer	0-100	Total required CAP utilization in percent	10

The MLME-ODGTS.request/confirm/indication primitives are basically following the format of the MLME-GTS.request/confirm/indication primitives, but a parameter, or *ODGTSCharacteristics*, is added for each primitives. Also, the MLME-ODCAP.request/indication are added for requesting CAP utilizations. Figure 7 shows the frame formats defined for the new primitives.

5. Performance evaluation

The performance of the CAP allocation algorithm for the OD-MAC is evaluated with NS2. CAP utilization, delivery ratio and energy efficiency are evaluated for analyzing the CAP performance. Also, the performance of proposed algorithm is compared with those of IEEE 802.15.4 MAC standard.

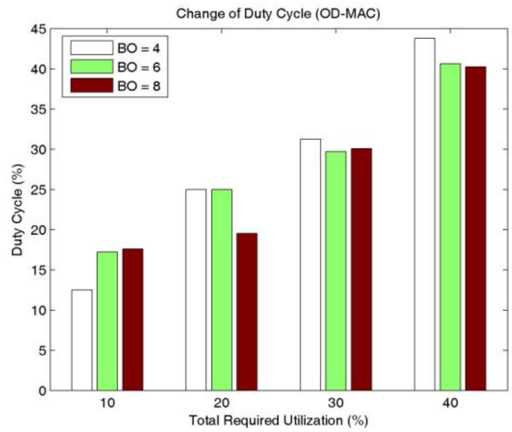
For the simulation, 10 nodes are used, 1 coordinator and 9 sensor nodes on star topology, and the sensor nodes are deployed with the same distance of 5m. Also, the sensor nodes transmit packets on 2.4GHz RF band for 10000 seconds of simulation time. Moreover, the performance of the CAP allocation algorithm is tested with three different beacon intervals in NS2 simulator. For the evaluation, duty cycle changes and delivery ratios of the OD-MAC and IEEE 802.15.4 MAC with different superframe durations (SD) are checked according to the total required utilizations from 10% to 40%. For three different BIs, BOs are set to 2, 4, and 6. Also, SO is set to 0, 2, and 4 for BO = 4, 0, 2, 4, and 6 for BO = 6, and 0, 2, 4, 6, and 8 for BO = 8. Moreover, energy efficiency is tested based on power consumption of TI CC2420 [2], the IEEE 802.15.4 compatible RF transceiver.

The network coordinator of the OD-MAC adjusts SD according to requests of bandwidth utilization from NRTMs. In other words, it allocates CAP slots based on the estimated total required utilization, and the duty cycles are being changed. It is depicted in Figure 8 (a). On the other hand, the duty cycles of IEEE 802.15.4 standard cannot change them dynamically. It sets SO at the initial stage and does not change them. Figure 8 (b) shows the duty cycles when BO = 4, 6, 8, and SO = 0, 2, 4, 6, 8. Some of the duty cycles of the OD-MAC had been over-allocated in some cases, and those are needed to be optimized with a new optimization algorithm.

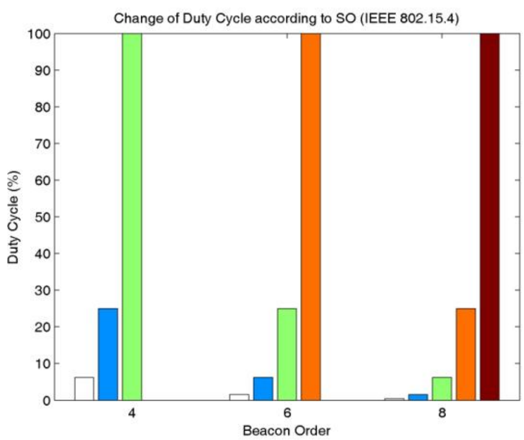
In Figure 9, delivery ratios of the two protocols are compared. The delivery ratio decreases slightly as the required utilization increases, and the OD-MAC achieved about 80 to 90 percent of delivery ratio. On the other hand, the delivery ratio of IEEE 802.15.4 MAC protocol, that with smaller SD than required utilization, decreases drastically. Also, SOs with 25% duty cycles (SO = 2 – BO = 4, SO = 4 – BO = 6, SO = 6 – BO = 8) show high delivery ratios until the duty cycle, but the delivery ratios are decreased when the TRU is over 25%. Only the results with 100% duty cycles show better performance than those of the OD-MAC.

In addition for evaluating the performance of CAP allocation algorithm, the energy efficiency is also tested with 10000 seconds of simulation time. The energy consumptions of one sensor node in different utilizations are estimated based on transmitting and receiving power consumption of CC2420 (Tx = 17.4mA at 0dBm, Rx = 18mA). The power consumption shall be estimated like (10). T_{SIM} means the simulation time, and P_{TX} and P_{RX} denote the transmission and receive power here.

$$E_i = SD * T_S * \left\lfloor \frac{T_{SIM}}{BI} \right\rfloor * P_{TX} * \frac{RU_i}{TRU_i} + SD * T_S * \left\lfloor \frac{T_{SIM}}{BI} \right\rfloor * P_{RX} * \frac{1 - RU_i}{TRU_i} \quad (10)$$

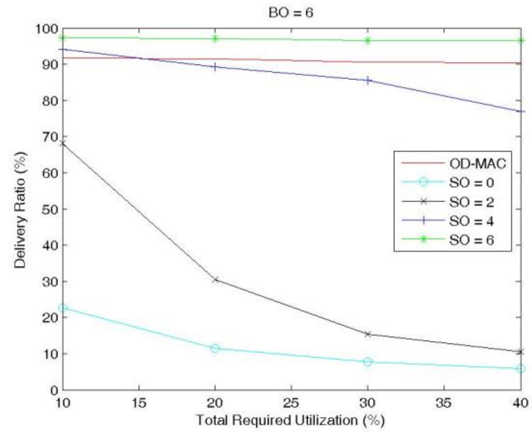


(a)



(b)

Figure 8. Changes of duty cyles



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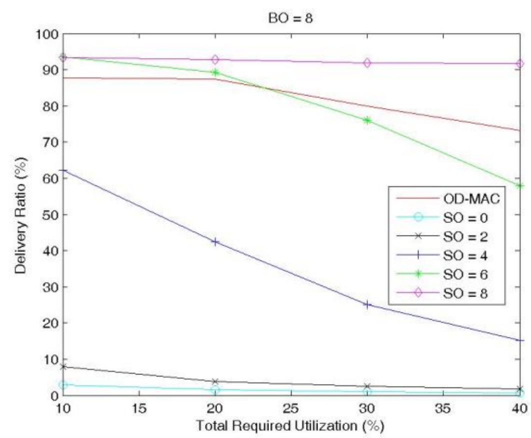
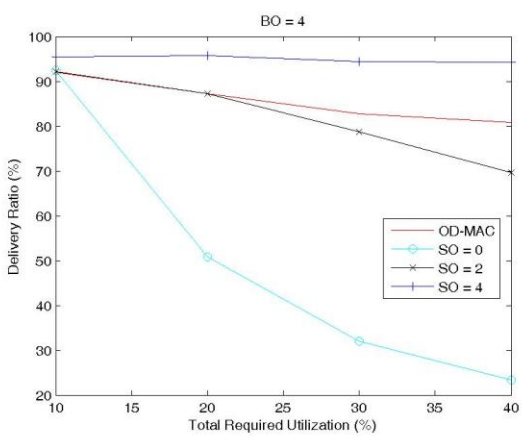


(c)

Figure 9. Delivery ratio of the OD-MAC and the standard



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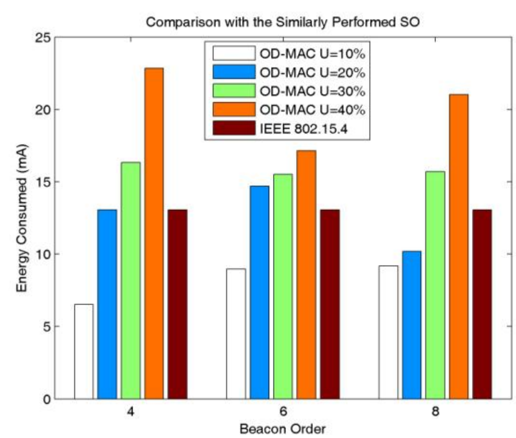

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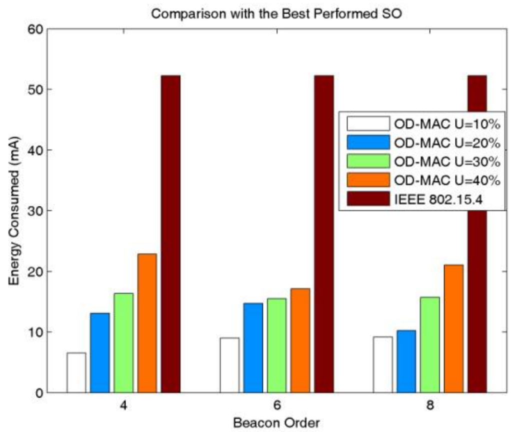

(b)

Figure 10. Comparison of energy consumption

Also, the performances of OD-MAC with 10 to 40% utilizations are compared to those of the similarly performed SOs (SO = 2 – BO = 4, SO = 4 – BO = 4, SO = 6, BO = 8) and the best performed SOs (SO = 4 – BO = 4, SO = 6 – BO = 6, SO = 8 – BO = 8) in each BO. In case of the comparison of similarly performed SO, the OD-MAC consumes more after about 25% of duty cycle because the duty cycles of the standards are assigned to 25%. We can see a trade-off in the result. On the other hand, the best performed SOs consume much more than two times of energy compare to the 40% of RTU of the OD-MAC.

6. Conclusion

The OD-MAC has been developed to satisfy requirements of MAC protocols for BSN: real-time transmission, collision avoidance, energy efficiency, and adaptivity.

The OD-MAC introduced the dynamic GTS scheduling algorithm with the schedulability checking. When the total utilization is less than 1, all the RTMs are schedulable. Also, it made the protocol to achieve real-time transmission and collision avoidance. Moreover, it showed better delivery ratio and energy efficiency than the standard protocol. The proposed protocol achieved about 80~90% of delivery ratio, and there was a trade-off between those two factors. However, this paper more focused on real-time transmission and collision avoidance, so the trade-off can be ignored. Moreover, these results proved the adaptivity of managing superframe structures.

In the future, standards of physical (PHY) layer should be defined to reflect the characteristics, such as RF bands and data rate, of BSNs, and MAC protocols need to be developed based on and optimized to the PHY standards.

8. References

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